

Forward Raman compression via photonic band gap in metals or warm dense matter

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The group velocity of a light pulse in photonic band gap material could considerably deviate from the speed of light in vacuum. Different speeds of a forward stoke and a pump pulse would enable the Raman compression in metals or the warm dense matter. A small window of the parameter regime, where the compression is feasible via the forward Raman scattering, is identified.

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The photonic band gap (PBG) material, consisting of periodic dielectric or metallo-dielectric structures, has strong interaction with the photons, leading to rich phenomena. It is widely used to manipulate the visible lights for various practical purposes [1]. It is shown that even the soft x-ray could be manipulated using the PBG [2]. In particular, it is noted that the group velocities of the pulses could be considerably different from each other.

Manipulating an x-ray becomes increasingly more important and practical, as advanced light sources make intense x-rays available for many applications [3–5]. The backward Raman scattering (BRS), which has been successful for the compression of the visible light, could make such intense x-rays even shorter and more intense in dense plasmas [6–9]. However, many physical processes to be considered for the x-ray compression in dense plasmas are different from those for visible lights in ideal plasmas, including the Fermi degeneracy [10, 11], the electron quantum diffraction [12], the electron band gap [2] and the plasmon decay [13], to mention a few. These different processes render some severe difficulties in the visible light BRS become harmless in the x-ray BRS, or vice versa. For example, the parasitic forward Raman scattering (FRS) might not be severe in dense plasmas [13–17].

The goal of this paper is to apply the photonic band gap concept and the aforementioned peculiar properties of dense plasmas to the forward Raman x-ray compression. We propose that the FRS could be used as a compressing mechanism, as opposed to being an obstacle for the compression. The thresholds for the pulse intensity and duration required for the compression are estimated.

We begin by considering a band gap material, consisting of alternating layers of two different kinds of metals (denoted by metal A and B below). Let $\delta\omega_{pe}^2 = 4\pi(n_A - n_B)e^2/m_e$ where n_A (n_B) is the electron density of the layer A (B). As discussed in Ref. [2], the band width of the pump pulse should be much smaller than the band gap, in order for a well-defined wave packet of the velocity to be considerably different from speed of

the light in vacuum. This condition imposes a constraint on the pulse duration [2]

$$\tau > 10 \left(\frac{\omega}{\omega_{pe}} \right)^2 \frac{1}{\omega}, \quad (1)$$

where $\omega_{pe}^2 = 4\pi n_B e^2/m_e$ and ω is the frequency of the light pulse. When the above conditions are satisfied, the FRS can be used as a compressing mechanism, as the seed and the pump pulses could travel with different velocities. If the seed and pump travel with the same velocity, the FRS cannot be used as a compressing channel.

The one-dimensional (1-D) equations describing the three-wave interactions of the Raman scattering in the PBG material reads [8]:

$$\begin{aligned} \left(\frac{\partial}{\partial t} + v_1 \frac{\partial}{\partial x} + \nu_1 \right) A_1 &= -ic_1 A_2 A_3 \\ \left(\frac{\partial}{\partial t} + v_2 \frac{\partial}{\partial x} + \nu_2 \right) A_2 &= -ic_2 A_1 A_3^* \\ \left(\frac{\partial}{\partial t} + v_3 \frac{\partial}{\partial x} + \nu_3 \right) A_3 &= -ic_3 A_1 A_2^*, \end{aligned} \quad (2)$$

where $A_1 = eE_1/m\omega_1 c$ (A_2) is the electron quiver velocity of the pump (seed) pulse scaled by the speed of light c , $A_3 = \tilde{n}_e/n_e$ is the Langmuir wave intensity; ν_1 (ν_2) is the rate of the inverse bremsstrahlung of the pump (seed), and ν_3 is the rate of the plasmon decay; $c_1 = \omega_{pe}^2/2\omega_1$, $c_2 = \omega_{pe}^2/2\omega_2$, $c_3 = (ck_3)^2/2\omega_3$; ω_1 (ω_2) is the frequency of the pump (seed), and $\omega_3 = \omega_{pe} = (4\pi n_e^2/m_e)^{1/2}$. The energy conservation relation in the FRS (BRS) is given as $\omega_1 = \omega_2 + \omega_{pe}$ and the momentum conservation is $k_3 = k_1 - k_2$ ($k_1 + k_2$). The plasmon decay rate $\nu_3(q)$ in metals, which is mainly attributed to the Umklapp processes [16], is much higher than the theoretical predictions based on the random phase approximation. The plasmon decay rate for $q < 0.5k_F$, where k_F is the Fermi wave vector, is given as

$$\nu_3(q) = \eta(q)\omega_{pe}, \quad (3)$$

where $\eta(k) = \eta_0 + d\eta/dq^2(q/k_F)^2$. For typical metal, $0.02 < \eta_0 < 0.2$ and $k_F^2 d\eta/dq^2 \cong a\eta_0$ ($2 < a < 10$) [14].

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More detailed discussion can be found in Ref. [18]. The inverse bremsstrahlung (ν_1 and ν_2) in metal is [19, 20]

$$\nu_B(\omega, E) = 4\pi n_i Z_i^2 \left(\frac{e^4}{m_e^2 v_F^3} \right) \frac{\omega_{pe}^2}{\omega^2} \frac{F(\alpha)}{s^2 \kappa^{1/2}}, \quad (4)$$

where it is assumed that $\kappa = (\hbar\omega/2m_e v_F^2) < 1$. v_F is the Fermi energy and $\alpha^2 = 2e^2 E^2 / m\hbar\omega^3$, where E is the electric field of the pulse. $F(\alpha)$ can be approximated as $F(\alpha) \cong \alpha^2/6$ when $\alpha < 2$ and $F(\alpha) \cong (2/\pi\alpha) \log(2\alpha)^2$ when $\alpha \geq 2$ [19].

In order for the pump to overcome the inverse bremsstrahlung, the minimum pump pulse duration τ given by Eq. (1) should be larger than the inverse bremsstrahlung decay time. This condition reads

$$\nu_B(\omega, E)\tau = \frac{40\pi n_i Z_i^2 \left(\frac{e^4}{m_e^2 v_F^3} \right) F(\alpha)}{\omega_1} \frac{F(\alpha)}{s^2 \kappa^{1/2}} \ll 1. \quad (5)$$

which is satisfied for most metal when $\omega_1/\omega_{pe} > 5$. From Eq. (2), the linear Raman growth condition from the FRS is estimated to be $c_2 c_3 |A_1|^2 > \nu_2 \nu_3$, where c_1 , c_2 and c_3 are assumed to be smaller by a factor of 2 compared to what is given in Eq. (2) (provided that the Raman interaction mainly arises from the dense layers). Then the threshold criteria for the FRS instability is given as

$$A_{1F}^2 = \frac{8.91 \times 10^{16} Z \text{ sec}}{\omega_{pe}} \eta(q) s_2^{-3/2} \log(2\alpha_2)^2 \left(\frac{\omega_{pe}}{\omega_2} \right). \quad (6)$$

where it is assumed that $\alpha > 2$. The condition, $A_1 > A_{1F}$, is necessary for the compression. For example, consider Aluminum (AL) with $\omega_1/\omega_{pe} = 10$ ($Z = 3$, $\eta \cong 0.03$, and $\omega_{pe} = 2.32 \times 10^{16} \text{ sec}^{-1}$). For $s_2 = 50$, which corresponds to the electron quiver energy (due to the seed pulse) of 500 eV and the laser intensity of $3.04 \times 10^{19} \text{ W/cm}^2$, the instability threshold of the pump field is $0.8 \times 10^{19} \text{ W/cm}^2$.

There could be a parasitic FRS from the background noise plasmon. As the noise seed is not intense enough ($\alpha < 2$), we use an approximate functional form $F(\alpha) \cong \alpha^2/6$. The growth rate of the noise instability from Eq. (2) is

$$\gamma = \frac{1}{16\eta} \frac{\omega_{pe}}{\omega_1} A_1^2 \omega_{pe}. \quad (7)$$

Assuming the seed has the duration of τ_p , the background FRS can have a growth factor at most $\exp(\tau_p \gamma)$. For $\omega_{pe}/\omega = 0.1$ and $\eta = 0.03$, this is estimated to be $\exp(0.2 A_1^2 (\omega_{pe} \tau_p))$. As long as $\tau_p < 50/A_1^2$, the background FRS cannot deplete the pump, which is the case due to the condition Eq. (5). Furthermore, the alternating layer would prevent this instability. The background plasmon (the pump) in the FRS has a wave vector of ω_{pe}/c (ω_1/c), where $\omega_1/\omega_{pe} \geq 5$. Let us assume that each layer has an excitation of a plasmon of the form $E_i \exp(ik_3 y - i\omega_{pe} t + i\theta_i)$, where θ_i is an independent phase between the layers. The amplitude of

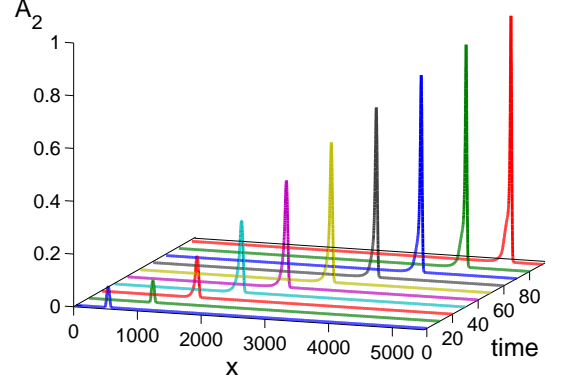


FIG. 1: The time evolution of the seed pulse, where t is normalized by $\omega_{pe} = 2.39 \times 10^{16} / \text{sec}$. The pump has duration of $4000/\omega_{pe}$, which corresponds to 173 femto second, and the electron quiver energy of 0.8 keV ($0.6 \times 10^{20} \text{ W/cm}^2$). The seed has the duration of 4 femto seconds with the quiver energy of 1.6 keV. The PBG material is located in $500 < x < 5000$, where x is normalized by $c/\omega_{pe} = 1.30 \times 10^{-6} \text{ cm}$.

$|\Sigma E_i E_j \exp(i(\theta_i - \theta_j))|^2$ is not proportional to N^2 but to N , where $N \cong 2\omega_1/\omega_{pe}$. This lack of coherence prevents the background noise FRS.

We demonstrate the estimation given by Eqs. (5) and (6) through 1-D simulation of Eq. (2) applied to AL. In the numerical integration of Eq. (2) (Fig. 1; the initial seed and pump pulses propagate to the right), where the seed is amplified by a factor of 80 in its intensity. It is assumed that the pump pulse has the group velocity $c/2$ and the seed has the velocity of c , which can be achieved by choosing the pump pulse frequency slightly below the band gap.

In the above simulation, it is assumed that the pump is slower than the seed (slow-pump): the seed pulse sweeps through the pump pulse and extracts the energy. It is also possible that the seed would be slower than the pump (slow-seed). For a highly intense pump, the inverse bremsstrahlung is a serious concern, where the slow-seed would be preferable because the part of the pump newly entering the PBG material will give out the energy to the seed before its energy gets dissipated by the inverse bremsstrahlung. For a moderately intense pump, the slow-pump might be better as it is easier to make the pump slower than the seed in the PBG material.

To summarize, the possibility of using the forward Raman scattering for the x-ray compression is examined. Our scheme is based on the fact that, in the PBG material, the forward stoke could have a different group velocity than the pump pulse. The background FRS would no longer be a big concern as a consequence of the strong decay of Langmuir waves. On the other hand, the strong inverse bremsstrahlung will put a limit on the pump pulse duration and increase the threshold intensity of the pump for Raman growth. We identify the plausible pulse char-

acteristics as given by Eqs. (1), (5) and (6).

In metal, the backward Raman scattering could be also plausible. Even though the excitation of the plasmon in the BRS is stronger than that in the FRS by a factor of $4(\omega/\omega_{pe})^2(\eta(\omega_{pe}/c)/\eta(2\omega/c))$, the BRS instability from

the noise plasmons is a severe problem. Furthermore, there is a maximum frequency limit ($2\omega/c \ll k_F$), over which the BRS compression is impossible. The FRS does not have such issues and therefore it is advantageous compared to the BRS in a very intense x-ray compression.

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